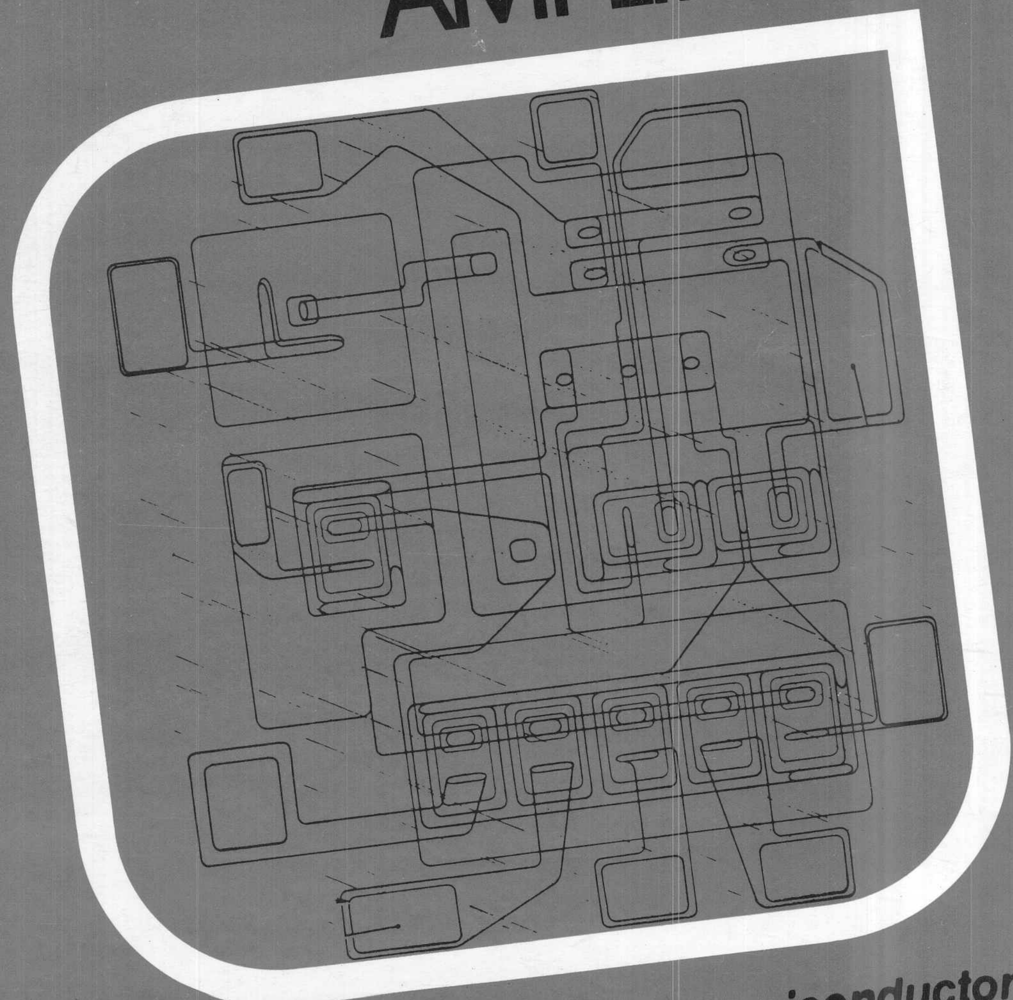
THE PROGRAMMABLE OPERATIONAL AMPLIFIERS



MOTOROLA Semiconductors

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Toulouse

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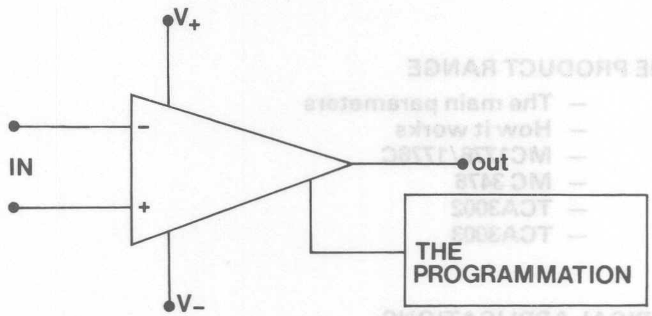
OPERATIONAL AMPLIFIERS

— **High Performance**

— **µ Power**
µ watts

— **Battery operation**



— This study describes why MOTOROLA have developped
Single and quads series of «Programmable operational amplifiers»
— The first, second and third chapters describe the THEORY of the operation and how the programmation system works
— The Fourth chapter describes the main applications («intrumentation» and «active filter»)
— The Last chapter explains the Theory of the circuit, describes the main parameters and details the MOTOROLA product range.
— SOME data sheets, curves and application of these circuits are also included.

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I — WHY A PROGRAMMABLE OP.AMP

— To meet market requirements for Low Power consumption wide bandwidth requirements, active filter applications, instrumentation medical, aviation equipment . . . The IC designer has seen some new contraints: «is it possible to use a single stock item for a variety of circuit functions in a system?»

This paper describes the circuit operation of the actual only solution «THE PROGRAMMABLE OPERATIONAL AMPLIFIER».

Basically a «Programmable Op.amp» is a highly versatile monolithic operational amplifier. A single external programming Resistor determines the quiescent power dissipation, input offset and bias currents, slew rate, gain bandwidth product, and input noise characteristics of the amplifier. This method allows the user to fix the program following the constraint of the design. For example, the user can trade-off supply current for bandwidth or optimize noise figure for a given source resistance.

II — THEORY OF THE OPERATION

— The single set resistor shown in Fig. 1 offers the most straight forward method of biasing a «Prog. op.amp». When the set resistor is connected from Pin 8 to ground the resistance value for a given set current is:

$$R_{SET} = \frac{V_{CC} - 0{,}6}{I_{Set}} \qquad (1)$$

— The 0,6 v shown in equation (1) is the voltage drop of the master bias current diode connected transistor on the integrated circuit chip.

— In applications where the regulation of the V^+ supply with respect to the V^- supply is better than the V^+ supply with respect to ground the set resistor should be connected like Fig. 2 and R_{Set} is then:

$$R_{SET} = \frac{V_{CC} - 0{,}6 - V_{EE}}{I_{Set}} \qquad (2)$$

R_{set} to GROUND

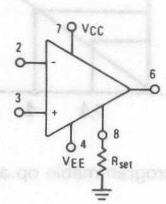


Fig. 1

Typical R_{set} Values		
V_{CC}, V_{EE}	I_{set} = 1.5 µA	I_{set} = 15 µA
±6.0V	3.6 MΩ	360 kΩ
±10V	6.2 MΩ	620 kΩ
±12V	7.5 MΩ	750 kΩ
±15V	10 MΩ	1.0 MΩ

R_{set} to NEGATIVE SUPPLY
(Recommended for supply voltage less than ±6.0 V)

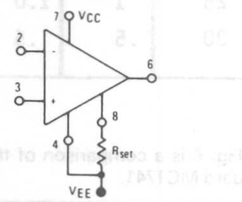


Fig. 2

Typical R_{set} Values		
V_{CC}, V_{EE}	Iset = 1.5 µA	I_{set} = 15 µA
±1.5V	1.6 MΩ	160 kΩ
±3.0V	3.6 MΩ	360 kΩ
±6.0V	7.5 MΩ	750 kΩ
±15 V	20 MΩ	2.0 MΩ

ACTIVE PROGRAMMING

BIPOLAR CURRENT SOURCE

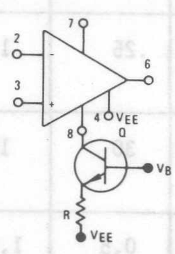


Fig. 3

FET CURRENT SOURCE

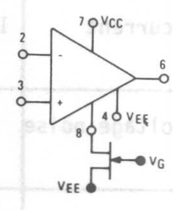


Fig. 4

Pins not shown are not connected.

— This biasing method with resistance is called «resistive programming», an other method called «active programming» is also possible.

The transistor and resistor scheme shown in Fig. 3 allows to switch the amplifier off without disturbing the main V^+ and V^- power supply connections. The transistor (Q) acts as an emitter follower current sink whose value depends on the control voltage V_B on the base. This circuit provides a method of varying the amplifier's characteristics over a limited range while the amplifier is in operation.
The FET circuit shown in fig 4 covers the full range of set currents in response to as little as a0,5v gate potential change on a low pinch-off voltage.

III – THE PROGRAMMATION

– Following the programmation described above you can select all the parameters of the characteristics shown Fig. 5.
– The gain bandwidth
– The slew rate
– The supply current
– The input bias current
– The input noise

Noise nV√HZ	BW MHZ	SR V/μs	IIB mA	IS (mA)
15	3	2	600	1
20	2	1,5	400	.50
25	1	1.0	200	.25
30	.5	.5	100	.15

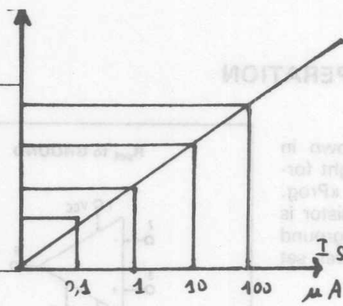


Fig. 5

– Fig. 6 is a comparison of the parameters of a programmable op.amp (TCA3002) versus those of the industry standard MC1741.

Characteristics	Symbol	Units	Programmable I_{SET} 8μA	Programmable I_{SET} 75μA	MC1741
Gain bandwidth	BW	MHz (typ)	.5	2.5	0,8
Input bias current	I_{IB}	nA (max)	200	500	500
Supply current	I_S	mA (max)	.25	1	2.8
Input voltage noise	En	nv√HZ (typ)	30	18	200
Slew Rate	SR	V/μs (typ)	0,5	1,2	.5

— more details are given Fig. 7.
These curves are the typical characteristics of the Quad programmable MOTOROLA op.amps TCA3002

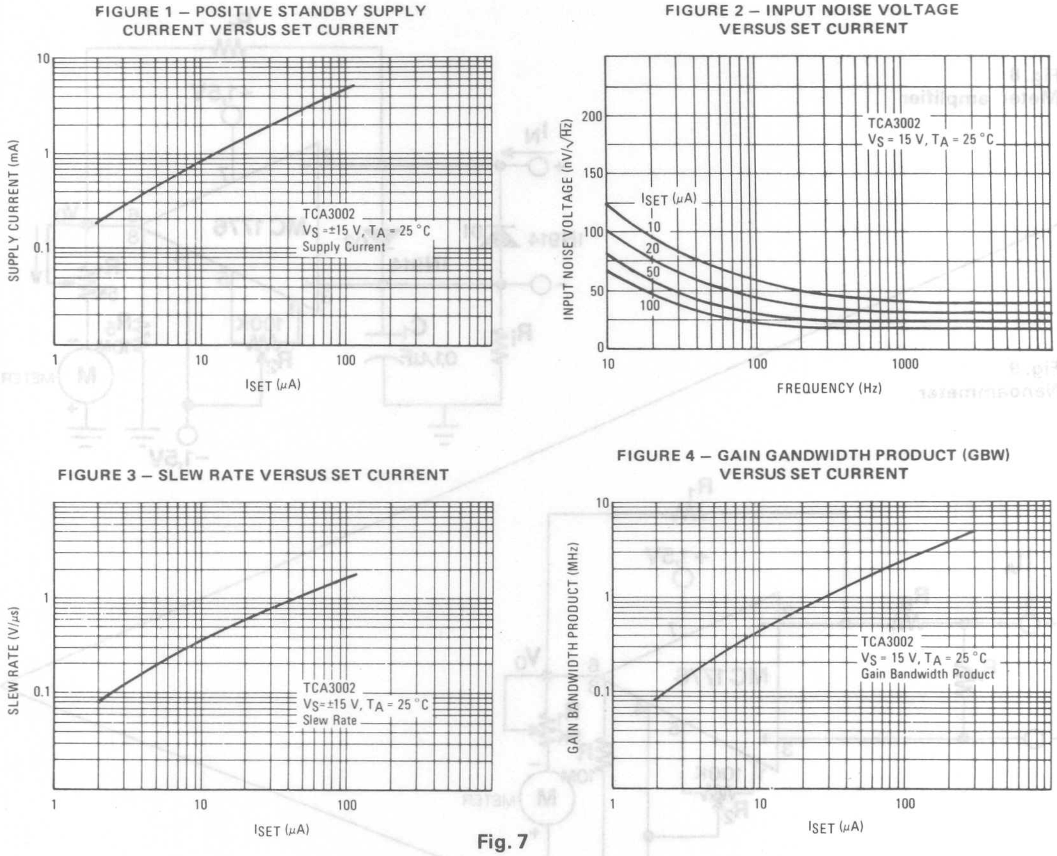


Fig. 7

IV — THE MAIN APPLICATIONS

The programmation is not the only advantage of this circuit. The input stage allows to have a common-mode input voltage which swings until 200 mV of the negative supply, the positive common-mode limit is typically 1,2 V below the positive supply voltage; this feature is especially useful in single supply operation with signals referred to ground ($\pm$ 1,2 V to $\pm$ 18 V supply operation).

The first evident application is **INSTRUMENTATION.**
Meter amplifier normally require one or two 9 V transistor batteries. Due to the heavy current drain on these supplies, the meters must be switched to the OFF position when not in use.
The meter circuit described here (Fig. 8) operates on two 1,5 V flash-light batteries and has a quiescent power drain so low that no on-off switch is needed. Fig. 9 shows a nanoammeter, the circuit will provide current range from 100 mA full scale to 100 μ A full scale.

A resistor (rv) inserted in series with one of the input full leads of the voltmeter (Fig. 10) converts it to a wide range voltmeter circuit. This inverting amplifier has a gain varying from – 30 (10 mV full scale) to – 0,003 (100 V full scale).

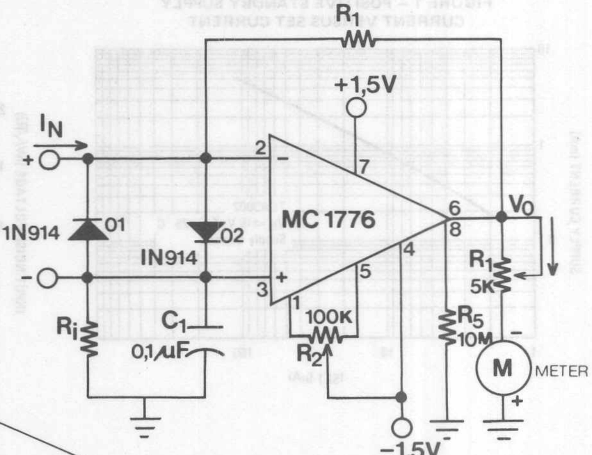


Fig. 8
Meter amplifier

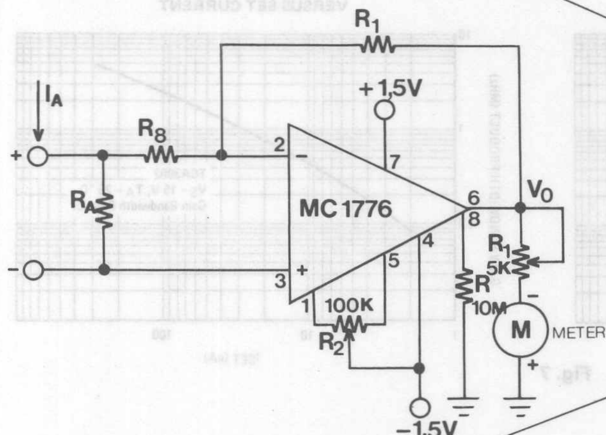


Fig. 9
Nanoammeter

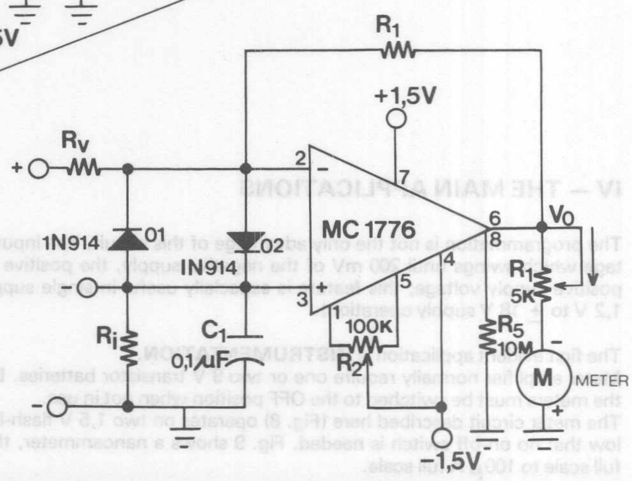


Fig. 10
Voltmeter

The most important applications are **ACTIVE FILTERS**
Frequency selective networks for use in the frequency range below 100 KHz have always been a problem. In this area of operation the required inductors and capacitors are large, both in value and physical size. The answer to this problem is to exchange the large inductor and capacitor for a large block of gain, and use well known feedback principles to achieve selectivity with RC active filters. Previously, to achieve a high degree of accuracy and circuit stability, a large number of active components was required in a fairly sophisticated circuit. Consequently, the design time and number of active components required made the use of active filter quite expensive.

The solutions of this problem are the «quad programmable op.amps». TCA3002 and TCA3003 fabricated at fairly reasonable costs. And as technology improves, the performance will continue to improve and the costs will continue to decline, making the use of active filter very economical.

Fig. 11

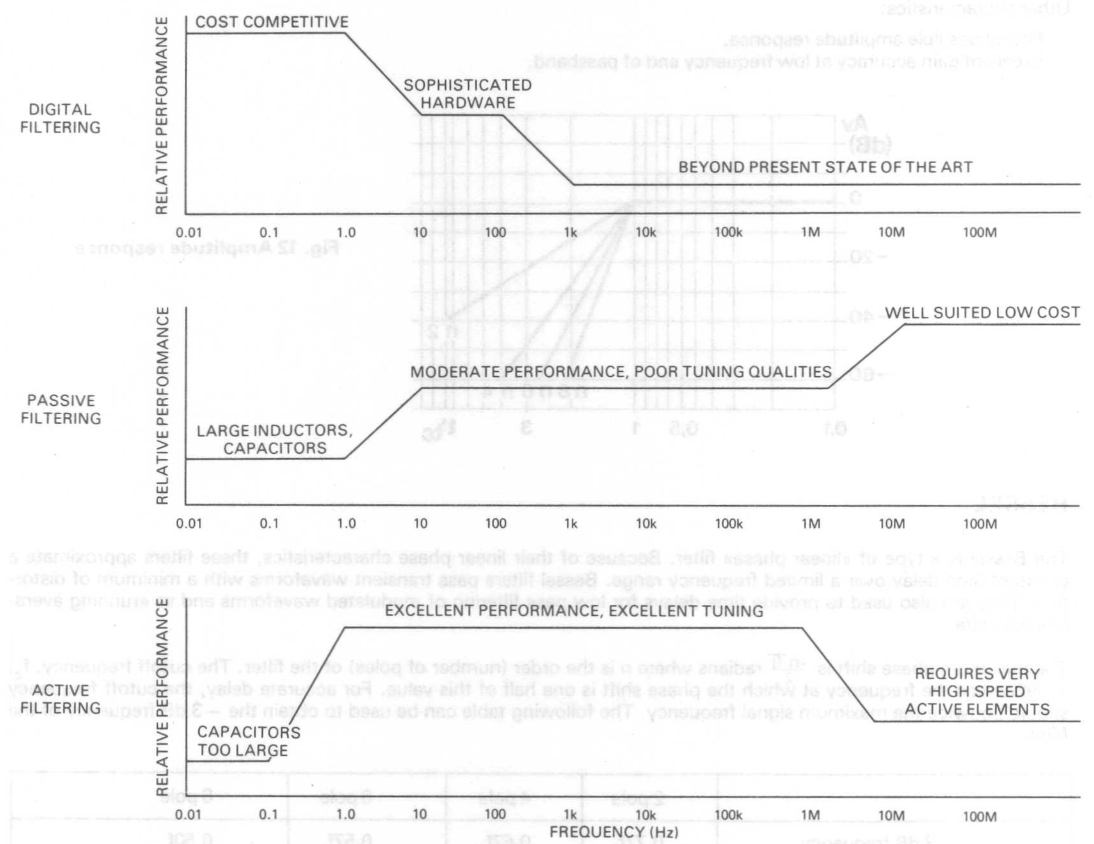


Fig. 11 compares active filters with digital and passive approaches as a function of frequency, and you can see that active filter are most useful in the 1 Hz to 1 MHz region.

Likewise digital filters are currently limited to below about 1 KHz and passive filters are most useful above 10 MHz.

Active filter function works like simple frequency selective control systems. Thus, you can create any desired filter characteristic by interconnecting integrators, inverters, summing amplifiers and lossy integrators.

Now the availability of low cost programmable single and quad Motorola op.amps have provided the active filter designer with the flexibility to externally program, to conceive various active filter types. Some of the more popular filters are multiple feedback; state variable, Sallen-Key and bi-quad which can be used to obtain high pass, band pass and low pass filter functions. However, these circuits are capable of giving the designer all the standard filter responses: Butterworth Bell, Chebyschev etc . . . You can see below a resume of the active low pass filter used.

Active low-pass filter: BUTTERWORTH

The Butterworth is a «maximally flat» amplitude response filter. Butterworth filters are used for filtering signals in data acquisition systems to prevent aliasing errors in sampled-data applications and for general purpose low-pass filtering. The cutoff frequency, f_c, is the frequency at which the amplitude response is down 3 dB. The attenuation rate beyond the cutoff frequency is 6 dB per octave of frequency where n is the order (number of poles) of the filter.

Other characteristics:

Flatest possible amplitude response.
Excellent gain accuracy at low frequency end of passband.

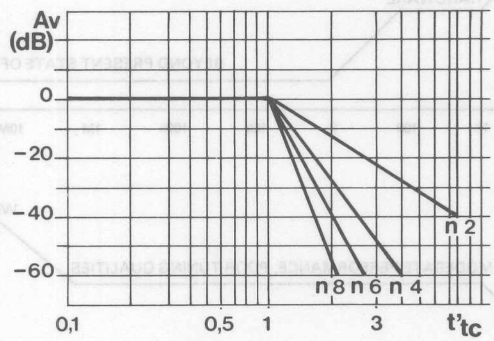


Fig. 12 Amplitude response

BESSEL

The Bessel is a type of «linear phase» filter. Because of their linear phase characteristics, these filters approximate a constant time delay over a limited frequency range. Bessel filters pass transient waveforms with a minimum of distortion. They are also used to provide time delays for low pass filtering of modulated waveforms and as «running average» type filter.

The maximum phase shift is $\frac{-n\pi}{2}$ radians where n is the order (number of poles) of the filter. The cutoff frequency, f_c, is defined as the frequency at which the phase shift is one half of this value. For accurate delay, the cutoff frequency should be twice the maximum signal frequency. The following table can be used to obtain the −3 dB frequency of the filter.

	2 pole	4 pole	6 pole	8 pole
−3 dB frequency	$0.77f_c$	$0.67f_c$	$0.57f_c$	$0.50f_c$

Other characteristics:

Selectivity not as great as Chebyschev or Butterworth.
Very little overshoot response to step inputs
Fast rise time.

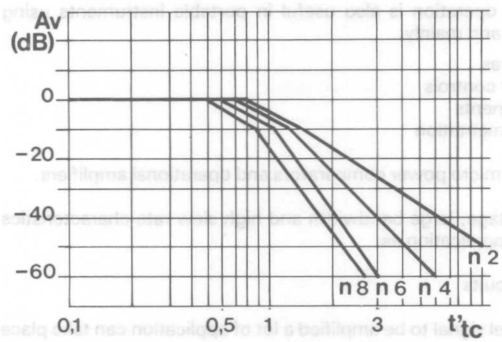


Fig. 13 Amplitude response

CHEBYSCHEV

Chebyschev filters have greater selectivity than either Bessel or Butter worth at the expense of ripple in the passband.
Chebyshev filters are normally designed with peak-to-peak ripple values from ± 0.2 dB to ± 2 dB.
Increased ripple in the passband allows increased attenuation above the cutoff frequency.
The cutoff frequency is defined as the frequency at which the amplitude response passes through the specified maximum ripple band and enters the stop band.

Other characteristics:

- Greater selectivity
- Very nonlinear phase response
- High overshoot response to step inputs

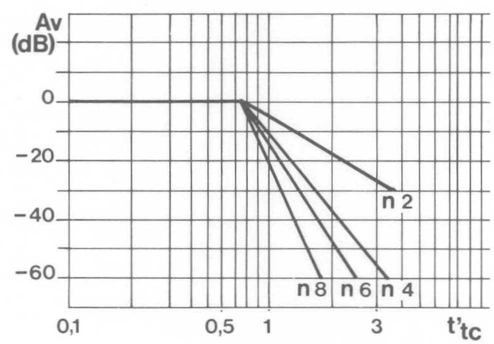


Fig. 14 Amplitude response
(± 1 dB ripple)

Due to the fact that these programmable amplifiers feature also advantages like:

— no latch up
— short circuit protection
— internal frequency compensation
— low cross over distorsion

Others applications can be considered like:

— medical
— voice activated switch and amplifier
— oscillator circuits
— aviation Instrumentation
— Pulse generator.

The micro power operation is also useful in portable instruments using battery operation, and mainly:

— portable cameras
— camera shutter controls
— aviation equipments
— portable instrumentation

These circuits use micro power comparators and operational amplifiers.

The low noise voltage, large bandwidth and high slew rate characteristics are well suited for application as:

— Transducer circuits

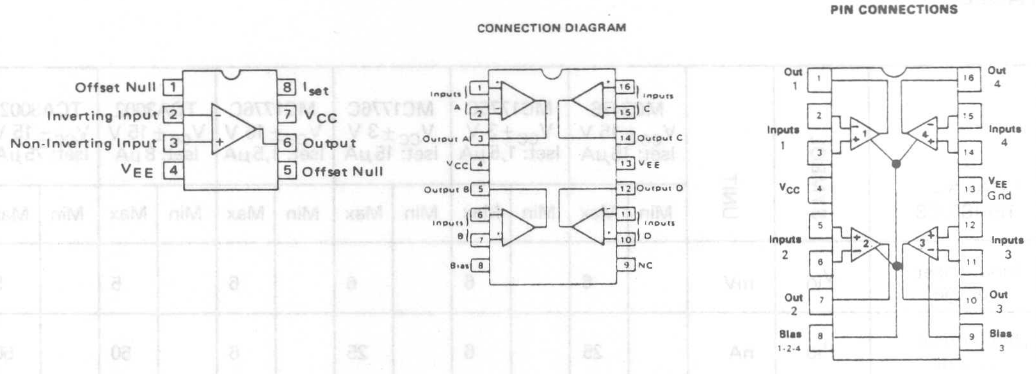
Due to the low level signal to be amplified a lot of application can take place on:

— audio circuits
— servo control circuits
— telephone amplifiers

V – THE PRODUCTS

Motorola have developped a range of 2 single and 2 quad programmable operational amplifiers (Fig. 15).

Fig. 15 MC3476/MC1776 TCA3002 TCA3003



a) The Product Range

The Table I resumes the Motorola «Programmable Operational Amplifier» product range.

TABLE I

DEVICE TYPE	PACKAGE	CASE	OPERATIING TEMPERATURE RANGE	FUNCTION	FEATURE
MC3476P1	Plastic	626	0 to +70° C	Single	Low cost
MC3476U	Ceramic	693	0 to +70° C	Single	Low cost
MC3476G	Metal can	601	0 to +70° C	Single	Low cost
MC1776G	Metal can	601	−55 to +125	Single	Military version
MC1776U	Ceramic	693	−55 to +125	Single	Military version
MC1776CG	Metal can	601	0 to +70° C	Single	MC3476 improved version
MC1776CP1	Plastic	626	0 to +70° C	Single	MC3476 improved version
MC1776CU	Ceramic	693	0 to +70° C	Single	MC3476 improved version
TCA3002DP	Plastic	648	0 to +70° C	Quad	4 op.amps programmable
TCA3002DC	Ceramic	620	0 to +70° C	Quad	together
TCA3003DP	Plastic	648	0 to +70° C	Quad	3 + 1 op.amps
TCA3003DC	Ceramic	620	0 to +70° C	Quad	Programmable separately

b) **The Main Parameters**

The Table II resumes on the most important parameters, versus different values of power supply voltage and I_{Set} current à 25° C.

TABLE II

CHARAC TERISTICS	SYMBOL	UNIT	MC3476 $V_{CC} \pm 15$ V Iset: 15 μA		MC1776C $V_{CC} \pm 3$ V Iset: 1,5 μA		MC1776C $V_{CC} \pm 3$ V Iset: 15 μA		MC1776C $V_{CC} \pm 15$ V Iset: 1,5 μA		TCA3002 $V_{CC} \pm 15$ V Iset: 8 μA		TCA3002 $V_{CC} \pm 15$ V Iset: 75 μA	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Input offset voltage	V_{IO}	mV		6		6		6		6		5		5
Input offset current	I_{IO}	nA		25		6		25		6		50		50
Input bias current	I_{IB}	nA		50		10		50		10		200		500
Supply current	I_{CC}	μA		200		170		30		190		1000		8000
Slew rate(typ.)	SR	V/μs	.8		.03		.35		.1		.3		1	

c) **How It Works**

— If you look at the Fig. 16 (example of the MC1776), regarding the **input stage** (pins 2 and 3) these products work like a conventional differential op.amp using lateral NPN's offset null capability (Pins 1 to 5) connected with a 100 k potentiometer allow the user to adjust the lowest input offset voltage.

— Q6 level shifts downward of the base of Q12 which is the **second stage** amplifier. Q12 is run as a common emitter amplifier with a current source load (Q4) to provide maximum gain. The output of Q12 drives the class B complementary **output stage** composed of Q11 and Q9.

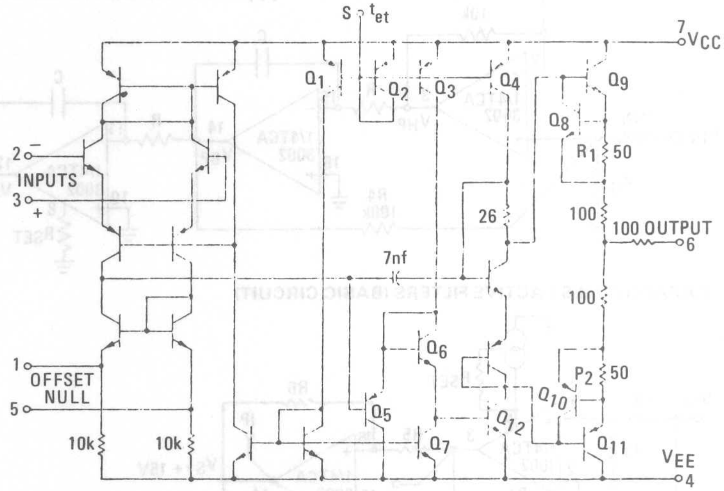


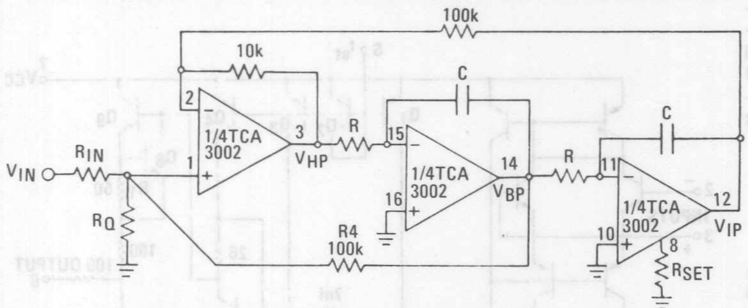
Fig. 16

— The **bias current** levels in the MC3476 are set by the amount of current (Iset) drawn out of pin 8. The constant current source Q2, Q3 and Q4 are controlled by the amount of Iset current through the transistor Q1 and external set resistor. Current source Q3 biases Q5 and Q6. The current source ratio between Q5 and Q6 is controlled by constant current sink Q7.

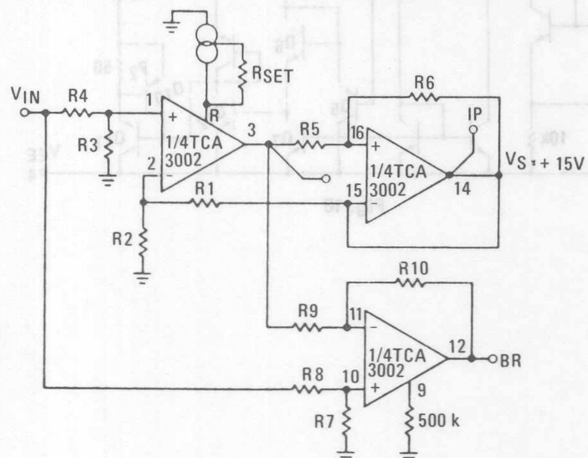
— The **output current** limiting is provided by Q8 and Q10 and their associated resistor R1 and R2. When enough current is drawn from the output, Q8 turn on and limits the base drive of Q9. Similary Q10 turn on when the MC3476 attempts to sink too much current, limiting the base drive of Q11 and therefore the output current. Frequency compensation is provided by the 30 pF capacitor across the second stage amplifier, Q12, of the MC3476.

VI – TYPICAL APPLICATIONS

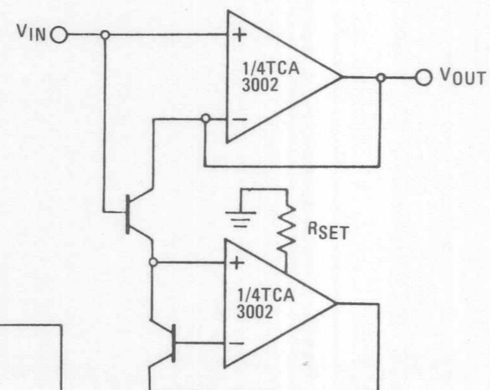
BASIC (NON-INVERTING «STATE VARIABLE») ACTIVE FILTER BUILDING BLOCK



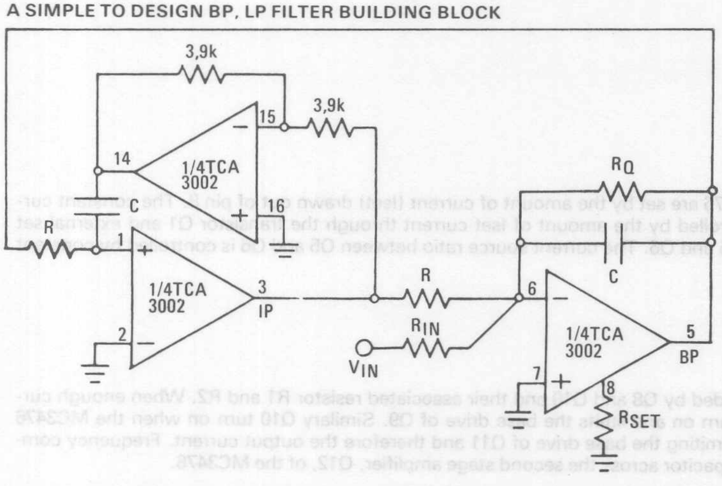
CAPACITORLESS ACTIVE FILTERS (BASIC CIRCUIT)



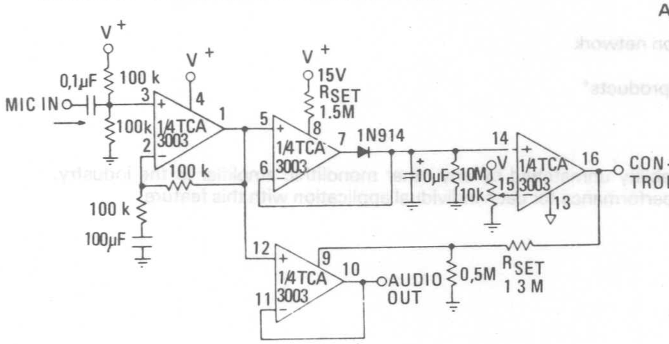
A UNITY GAIN FOLLOWER WITH BIAS CURRENT REDUCTION



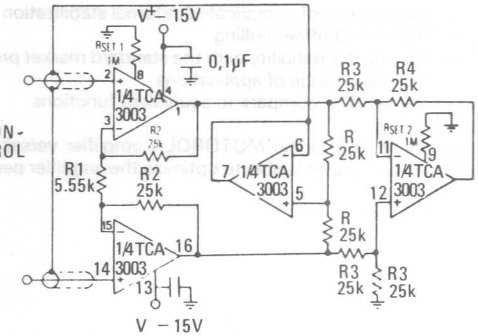
A SIMPLE TO DESIGN BP, LP FILTER BUILDING BLOCK



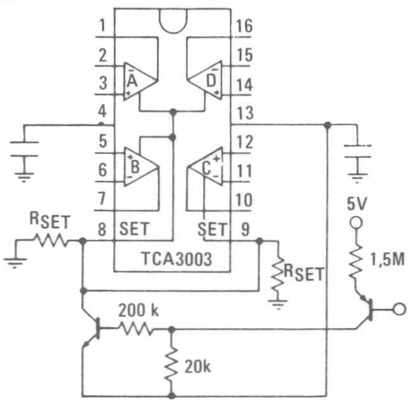
VOICE ACTIVATED SWITCH AND AMPLIFIER



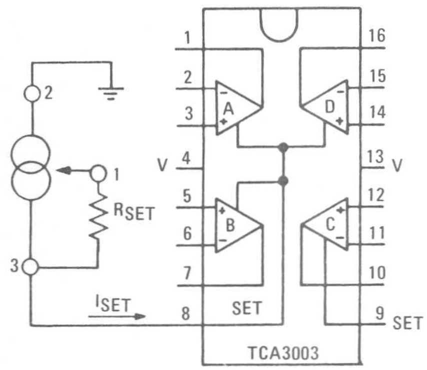
X10 MICROPOWER INSTRUMENTATION AMPLIFIER WITH BUFFERED INPUT GUARDING



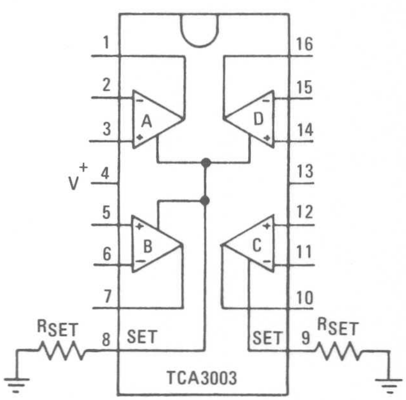
CIRCUIT SHUTDOWN



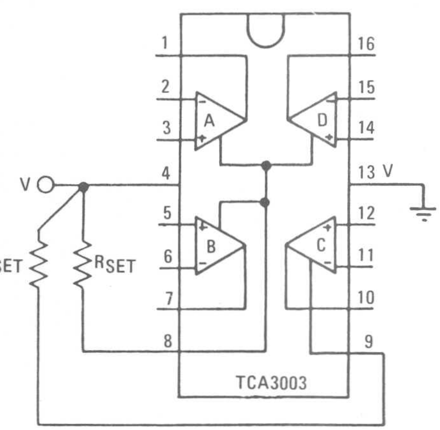
CURRENT SOURCE BIASING WITH TEMPERATURE COMPENSATION



DUAL SUPPLY OR NEGATIVE SUPPLY BIASING



SINGLE (POSITIVE) SUPPLY BIASING



VII – CONCLUSION

– The absence of complicated external stabilization network
– The ease of offset nulling
– The pin compatibility with the standard market products*
– The broad range of applications
– The low cost compare to equivalent functions

Combine to give the MOTOROLA amplifier versability unmatched by any other monolithic amplifier in the industry. However the user is able to optimize the amplifier performance for each individual application with this feature.

*MC1776, MC1776C, MC3476 are pin to pin equivalent with the industry standard MC1741/μa741
TCA3003 is pin to pin equivalent with the industry standard MC3403/LM324 (except for the two programming pins at the bottom of the package).